

NAVIGATING A UAV WITH A REMOTE CONTROL DEVICE

Inventors: William Kress Bodin

5

Jesse J.W. Redman

Derral C. Thorson

BACKGROUND OF THE INVENTION

10

Field of the Invention

The field of the invention is data processing, or, more specifically, methods, systems, and products for navigating a UAV.

15

Description Of Related Art

Many forms of UAV are available in prior art, both domestically and internationally.

Their payload weight carrying capability, their accommodations (volume,

20 environment), their mission profiles (altitude, range, duration), and their command, control and data acquisition capabilities vary significantly. Routine civil access to these various UAV assets is in an embryonic state.

Conventional UAVs are typically manually controlled by an operator who may view

25 aspects of a UAV's flight using cameras installed on the UAV with images provided through downlink telemetry. Navigating such UAVs from a starting position to one or more waypoints requires an operator to have specific knowledge of the UAV's

flight, including such aspects as starting location, the UAV's current location, waypoint locations, and so on. Operators of prior art UAVs usually are required generally to manually control the UAV from a starting position to a waypoint with little aid from automation. There is therefore an ongoing need for improvement in the 5 area of UAV navigations.

SUMMARY OF THE INVENTION

Methods, systems, and products are described for UAV navigation that enable an operator to input a single interface operation, a mouseclick or joystick button click, thereby selecting GUI pixel from a displayed map of the surface of the Earth. The selected pixel maps to a waypoint. Flight control instructions are uploaded through uplink telemetry to a UAV which flies a course to the waypoint. The heading is not necessarily the course if wind is present, depending on the navigation algorithm chosen for the flight. All this may occur with a single keystroke or mouseclick from the operator.

In addition to uplinking a single waypoint, operators of remote control devices according to embodiments of the present invention are enabled to enter through a user interface and store in the remote control device many waypoints which taken in sequence form an entire mission for a UAV that flies from waypoint to waypoint, eventually returning to a starting point. In addition to providing for a mission route comprising many waypoints, typical embodiments also support ‘macros,’ sets of UAV instructions associated with waypoints. Such UAV instructions can include, for example, instructions to orbit, take photographs or stream video, and continue flying a route or mission to a next waypoint. Because waypoints are entered with selected pixels and macros may be created by selecting UAV instructions from a pull down menu in a GUI, complex missions may be established with a few keystrokes of mouseclicks on an interface of a remote control device.

25

More particularly, methods, systems, and products are disclosed in this specification for navigating a UAV. Typical embodiments include receiving in a remote control

device a user's selection of a GUI map pixel that represents a waypoint for UAV navigation, the pixel having a location on the GUI; mapping the pixel's location on the GUI to Earth coordinates of the waypoint; receiving a starting position from a GPS receiver on the UAV; calculating a heading in dependence upon the starting position, the coordinates of the waypoint, and a navigation algorithm; identifying flight control instructions for flying the UAV on the heading; and transmitting the flight control instructions from the remote control device to the UAV.

5 Typical embodiments often also include receiving user selections of a multiplicity of GUI map pixels representing waypoints, where each pixel has a location on the GUI; mapping each pixel location to Earth coordinates of a waypoint; assigning one or more UAV instructions to each waypoint; storing the coordinates of the waypoints and the UAV instructions in computer memory on the remote control device; flying the UAV to each waypoint in accordance with one or more navigation algorithms;

10 15 and operating the UAV at each waypoint in accordance with the UAV instructions for each waypoint, including: identifying flight control instructions in dependence upon the UAV instructions for each waypoint; and transmitting the flight control instructions from the remote control device to the UAV.

20 In typical embodiments, mapping the pixel's location on the GUI to Earth coordinates of the waypoint further includes mapping pixel boundaries of the GUI map to Earth coordinates; identifying a range of latitude and a range of longitude represented by each pixel; and locating a region on the surface of the Earth in dependence upon the boundaries, the ranges, and the location of the pixel on the GUI map. In typical

25 embodiments, locating a region on the surface of the Earth in dependence upon the boundaries, the ranges, and the location of the pixel on the GUI map further includes: multiplying the range of longitude represented by each pixel by a column number of

the selected pixel, yielding a first multiplicand; multiplying the range of longitude represented by each pixel by 0.5, yielding a second multiplicand; adding the first and second multiplicands to an origin longitude of the GUI map; multiplying the range of latitude represented by each pixel by a row number of the selected pixel, yielding a

- 5 third multiplicand; multiplying the range of latitude represented by each pixel by 0.5, yielding a fourth multiplicand; and adding the third and fourth multiplicands to an origin latitude of the GUI map.

Many embodiments also include periodically repeating the steps of: receiving in the

- 10 remote control device from the GPS receiver a current position of the UAV; calculating a new heading from the current position to the waypoint; identifying flight control instructions for flying the UAV on the new heading; and transmitting, from the remote control device to the UAV, the flight control instructions for flying the UAV on the new heading. Many embodiments include identifying a cross track
- 15 between the starting point and the waypoint, and periodically repeating the steps of: receiving in the remote control device from the GPS receiver a current position of the UAV; calculating a shortest distance between the current position and the cross track; and, if the shortest distance between the current position and the cross track is greater than a threshold distance, transmitting flight control instructions that pilot the UAV
- 20 toward the cross track; and, when the UAV arrives at the cross track, transmitting flight control instructions that pilot the UAV in a cross track direction toward the waypoint. In many embodiments, calculating a shortest distance between the current position and the cross track includes: calculating the distance from the current position to the waypoint; calculating the angle between a direction from the current
- 25 position to the waypoint and a cross track direction; calculating the tangent of the angle; and multiplying the tangent of the angle by the distance from the current position to the waypoint.

Many embodiments include identifying a cross track having a cross track direction between the starting point and the waypoint and periodically repeating the steps of: receiving in the remote control device from the GPS receiver a current position and a

- 5 current heading of the UAV; calculating an angle between the direction from the current position to the waypoint and a cross track direction; and, if the angle is greater than a threshold angle, transmitting flight control instructions that pilot the UAV toward the cross track, and, upon arriving at the cross track, transmitting flight control instructions that pilot the UAV in the cross track direction toward the waypoint. In
- 10 such embodiments, the threshold angle often is implemented as a variable whose value varies in dependence upon a distance between the UAV and the waypoint.

Many embodiments also include periodically repeating the steps of: receiving in the remote control device from the GPS receiver a current position of the UAV;

- 15 calculating a direction to the waypoint from the current position; calculating a heading in dependence upon wind speed, wind direction, air speed, and the direction to the waypoint; transmitting flight control instructions for turning the UAV to the heading; and transmitting flight control instructions for flying the UAV on the heading. Many embodiments also include identifying a cross track; calculating a
- 20 cross track direction from the starting position to the waypoint; and periodically repeating the steps of: receiving in the remote control device from the GPS receiver a current position of the UAV; calculating a shortest distance between the cross track and the current position; and, if the shortest distance between the cross track and the current position is greater than a threshold distance, transmitting flight control
- 25 instructions for piloting the UAV to the cross track. Such embodiments typically include the following steps to be carried out when the UAV arrives at the cross track: receiving in the remote control device from the GPS receiver a new current position

of the UAV; calculating, in dependence upon wind speed, wind direction, air speed, and the cross track direction, a new heading; transmitting flight control instructions for turning the UAV to the new heading; and transmitting flight control instructions for flying the UAV on the new heading.

5

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular descriptions of exemplary embodiments of the invention as illustrated in the accompanying drawings wherein like reference numbers generally represent like parts of exemplary embodiments of the invention.

10

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 sets forth a system diagram illustrating relations among components of an exemplary system for navigating a UAV.

5

Figure 2 is a block diagram of an exemplary UAV showing relations among components of included automated computing machinery.

10 Figure 3 is a block diagram of an exemplary remote control device showing relations among components of included automated computing machinery.

Figure 4 sets forth a flow chart illustrating an exemplary method for navigating a UAV that includes receiving in a remote control device a user's selection of a GUI map pixel that represents a waypoint for UAV navigation.

15

Figure 5 sets forth a block diagram that includes a GUI displaying a map and a corresponding area of the surface of the Earth.

20 Figure 6 sets forth a flow chart illustrating an exemplary method of navigating a UAV in accordance with a navigation algorithm.

Figure 7 sets forth a line drawing illustrating a flight path produced by application of the method of Figure 6.

25 Figure 8 sets forth a flow chart illustrating an exemplary method of navigating a UAV in accordance with a navigation algorithm.

Figure 9 sets forth a line drawing illustrating a flight path produced by application of the method of Figure 8.

5 Figure 10 sets forth a flow chart illustrating an exemplary method of navigating a UAV in accordance with a navigation algorithm.

Figure 11 sets forth a line drawing illustrating a flight path produced by application of the method of Figure 10.

10 Figure 12 sets forth a flow chart illustrating an exemplary method of navigating a UAV in accordance with a navigation algorithm.

Figure 12A sets forth a line drawing illustrating a method of calculating a heading with a cross wind to achieve a particular ground course.

15 Figure 13 sets forth a line drawing illustrating a flight path produced by application of the method of Figure 12.

20 Figure 14 sets forth a flow chart illustrating an exemplary method of navigating a UAV in accordance with a navigation algorithm.

Figure 15 sets forth a line drawing illustrating a flight path produced by application of the method of Figure 14.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

5

Introduction

The present invention is described to a large extent in this specification in terms of methods for navigating a UAV. Persons skilled in the art, however, will recognize that any computer system that includes suitable programming means for operating in accordance with the disclosed methods also falls well within the scope of the present invention. Suitable programming means include any means for directing a computer system to execute the steps of the method of the invention, including for example, systems included of processing units and arithmetic-logic circuits coupled to computer memory, which systems have the capability of storing in computer memory, which computer memory includes electronic circuits configured to store data and program instructions, programmed steps of the method of the invention for execution by a processing unit.

The invention also may be embodied in a computer program product, such as a diskette or other recording medium, for use with any suitable data processing system. Embodiments of a computer program product may be implemented by use of any recording medium for machine-readable information, including magnetic media, optical media, or other suitable media. Persons skilled in the art will immediately recognize that any computer system having suitable programming means will be capable of executing the steps of the method of the invention as embodied in a program product. Persons skilled in the art will recognize immediately that, although most of the exemplary embodiments described in this specification are oriented to

software installed and executing on computer hardware, nevertheless, alternative embodiments implemented as firmware or as hardware are well within the scope of the present invention.

5

Definitions

“Air speed” means UAV air speed, the speed of the UAV through the air.

10 A “cross track” is a fixed course from a starting point directly to a waypoint. A cross track has a direction, a ‘cross track direction,’ that is the direction straight from a starting point to a waypoint. That is, a cross track direction is the heading that a UAV would fly directly from a starting point to a waypoint in the absence of wind.

15 “GUI” means graphical user interface, a display means for a computer screen.

15

“Heading” means the compass heading of the UAV. “Course” means the direction of travel of the UAV over the ground. In the absence of wind, or in the presence of a straight tailwind or straight headwind, the course and the heading are the same direction. In the presence of crosswind, the course and the heading are different directions.

20 “Position” refers to a location in the air or over the ground. ‘Position’ is typically specified as Earth coordinates, latitude and longitude. A specification of position may also include altitude.

25

A “waypoint” is a position chosen as a destination for navigation of a route. A route has one or more waypoints. That is, a route is composed of waypoints, including at

least one final waypoint, and one or more intermediate waypoints.

“TDMA” stands for Time Division Multiple Access, a technology for delivering digital wireless service using time-division multiplexing. TDMA works by dividing a

5 radio frequency into time slots and then allocating slots to multiple calls. In this way, a single frequency can support multiple, simultaneous data channels. TDMA is used by GSM.

“GSM” stands for Global System for Mobile Communications, a digital cellular

10 standard. GSM at this time is the de facto standard for wireless digital communications in Europe and Asia.

“CDPD” stands for Cellular Digital Packet Data, a data transmission technology developed for use on cellular phone frequencies. CDPD uses unused cellular

15 channels to transmit data in packets. CDPD supports data transfer rates of up to 19.2 Kbps.

“GPRS” stands for General Packet Radio Service, a standard for wireless data communications which runs at speeds up to 150 Kbps, compared with current GSM

20 systems which cannot support more than about 9.6 Kbps. GPRS, which supports a wide range of speeds, is an efficient use of limited bandwidth and is particularly suited for sending and receiving small bursts of data, such as e-mail and Web browsing, as well as large volumes of data.

25 “EDGE” stands for Enhanced Data Rates for GSM Evolution, a standard for wireless data communications supporting data transfer rates of more than 300 Kbps. GPRS and EDGE are considered interim steps on the road to UMTS.

“UMTS” stands for Universal Mobile Telecommunication System, a standard for wireless data communications supporting data transfer rates of up to 2 Mpbs. UMTS is also referred to W-CDMA for Wideband Code Division Multiple Access.

5

Navigating a UAV with a Remote Control Device

Methods, systems, and products for navigating a UAV are explained with reference to the accompanying drawings, beginning with Figure 1. Figure 1 sets forth a system 10 diagram illustrating relations among components of an exemplary system for navigating a UAV. The system of Figure 1 includes UAV (100) which includes a GPS (Global Positioning System) receiver (not shown) that receives a steady stream of GPS data from satellites (190, 192). For convenience of explanation, only two GPS satellites are shown in Figure 1, although the GPS satellite network in fact 15 includes 24 GPS satellites.

The system of Figure 1 operates to navigate a UAV by receiving in a remote control device a user's selection of a GUI map pixel that represents a waypoint for UAV navigation. Each such pixel has a location on a GUI map, typically specified as a row 20 and column position. Examples of remote control devices in Figure 1 include mobile telephone (110), workstation (104), laptop computer (116), and PDA (Personal Digital Assistant) (120). Each such remote control device is capable of supporting a GUI display of a map of the surface of the Earth in which each pixel on the GUI map represents a position on the Earth.

25

Each remote control device also supports at least one user input device through which a user may enter the user's selection of a pixel. Examples of user input devices in the

system of Figure 1 include telephone keypad (122), workstation keyboard (114), workstation joystick (112), laptop keyboard (116) and PDA touch screen (118).

The system of Figure 1 typically is capable of operating a remote control device to
5 map the pixel's location on the GUI to Earth coordinates of a waypoint and receiving
a starting position from a GPS receiver on the UAV. In fact, the remote control
device is receiving downlink telemetry that includes a steady stream of GPS positions
of the UAV. Receiving a starting position therefore is typically carried out by taking
the current position of the UAV when the user selects the pixel as the starting
10 position. In the example of Figure 1, the remote control device generally receives
the starting position from the UAV through wireless network (102).

Wireless network (102) is implemented using any wireless data transmission
technology as will occur to those of skill in the art including, for example, TDMA,
15 GSM, CDPD, GPRS, EDGE, and UMTS. In a one embodiment, a data
communications link layer is implemented using one of these technologies, a data
communications network layer is implemented with the Internet Protocol ("IP"), and
a data communications transmission layer is implemented using the Transmission
Control Protocol ("TCP"). In such systems, telemetry between the UAV and remote
20 control devices, including starting positions, are transmitted using an application-
level protocol such as, for example, the HyperText Transmission Protocol ("HTTP"),
the Wireless Application Protocol ("WAP"), the Handheld Device Transmission
Protocol ("HDTP"), or any other data communications protocol as will occur to those
of skill in the art.

25

The system of Figure 1 typically is capable of calculating a heading in dependence
upon the starting position, the coordinates of the waypoint, and a navigation

algorithm, identifying flight control instructions for flying the UAV on the heading, and transmitting (420) the flight control instructions from the remote control device to the UAV.

5 UAVs according to embodiments of the present invention typically include, not only an aircraft, but also automated computing machinery capable of receiving GPS data, operating telemetry between the UAV and one or more remote control devices, and navigating a UAV among waypoints. Figure 2 is a block diagram of an exemplary UAV showing relations among components of included automated computing

10 machinery. In Figure 2, UAV (100) includes a processor (164), also typically referred to as a central processing unit or 'CPU.' The processor may be a microprocessor, a programmable control unit, or any other form of processor useful according to the form factor of a particular UAV as will occur to those of skill in the art. Other components of UAV (100) are coupled for data transfer to processor (164)

15 through system bus (100).

UAV (100) includes random access memory or 'RAM' (166). Stored in RAM (166) is an application program (158) that implements inventive methods according to embodiments of the present invention. In some embodiments, the application

20 programming runs on an OSGi services framework (156). OSGi Stands for 'Open Services Gateway Initiative.' The OSGi specification is a Java-based application layer framework that provides vendor neutral application layer APIs and functions. An OSGi service framework (126) is written in Java and therefore typically runs on a Java Virtual Machine (JVM) (154) which in turn runs on an operating system (150).

25 Examples of operating systems useful in UAVs according to the present invention include Unix, AIX_{TM}, and Microsoft Windows_{TM}.

In OSGi, the framework is a hosting platform for running ‘services’. Services are the main building blocks for creating applications according to the OSGi. A service is a group of Java classes and interfaces that implement a certain feature. The OSGi specification provides a number of standard services. For example, OSGi provides a

5 standard HTTP service that can respond to requests from HTTP clients, such as, for example, remote control devices according to embodiments of the present invention. That is, such remote control devices are enabled to communicate with a UAV having an HTTP service by use of data communications messages in the HTTP protocol.

10 Services in OSGi are packaged in ‘bundles’ with other files, images, and resources that the services need for execution. A bundle is a Java archive or ‘JAR’ file including one or more service implementations, an activator class, and a manifest file. An activator class is a Java class that the service framework uses to start and stop a bundle. A manifest file is a standard text file that describes the contents of the

15 bundle.

The services framework in OSGi also includes a service registry. The service registry includes a service registration including the service’s name and an instance of a class that implements the service for each bundle installed on the framework and registered

20 with the service registry. A bundle may request services that are not included in the bundle, but are registered on the framework service registry. To find a service, a bundle performs a query on the framework’s service registry.

25 In the UAV (100) of Figure 2, software programs and other useful information may be stored in RAM or in non-volatile memory (168). Non-volatile memory (168) may be implemented as a magnetic disk drive such as a micro-drive, an optical disk drive, static read only memory (‘ROM’), electrically erasable programmable read-only

memory space ('EEPROM' or 'flash' memory), or otherwise as will occur to those of skill in the art.

UAV (100) includes communications adapter (170) implementing data

- 5 communications connections (184) to other computers (162), which may be wireless networks, satellites, remote control devices, servers, or others as will occur to those of skill in the art. Communications adapter (170) advantageously facilitates receiving flight control instructions from a remote control device. Communications adapters implement the hardware level of data communications connections through which
- 10 UAVs transmit wireless data communications. Examples of communications adapters include wireless modems for dial-up connections through wireless telephone networks.

UAV (100) includes servos (178). Servos (178) are proportional control servos that

- 15 convert digital control signals from system bus (160) into actual proportional displacement of flight control surfaces, ailerons, elevators, and the rudder. The displacement of flight control surfaces is 'proportional' to values of digital control signals, as opposed to the 'all or nothing' motion produced by some servos. In this way, ailerons, for example, may be set to thirty degrees, sixty degrees, or any other
- 20 supported angle rather than always being only neutral or fully rotated. Several proportional control servos useful in various UAVs according to embodiments of the present invention are available from Futaba®.

UAV (100) includes a servo control adapter (172). A servo control adapter (172) is

- 25 multi-function input/output servo motion controller capable of controlling several servos. An example of such a servo control adapter is the "IOSERVO" model from National Control Devices of Osceola, Missouri. The IOSERVO is described on

National Control Devices website at www.controlanything.com.

UAV (100) includes a flight stabilizer system (174). A flight stabilizer system is a control module that operates servos (178) to automatically return a UAV to straight and level flight, thereby simplifying the work that must be done by navigation algorithms. An example of a flight stabilizer system useful in various embodiments of UAVs according to the present invention is model Co-Pilot_{TM} from FMA, Inc., of Frederick, Maryland. The Co-Pilot flight stabilizer system identifies a horizon with heat sensors, identifies changes in aircraft attitude relative to the horizon, and sends corrective signals to the servos (178) to keep the UAV flying straight and level.

UAV (100) includes an AVCS gyro (176). An AVCS gyro is an angular vector control system gyroscope that provides control signal to the servos to counter undesired changes in attitude such as those caused by sudden gusts of wind. An example of an AVCS gyro useful in various UAVs according to the present invention is model GYA350 from Futaba®.

Remote control devices according to embodiments of the present invention typically include automated computing machinery capable of receiving user selections of pixel on GUI maps, mapping the pixel to a waypoint location, receiving a starting position from a GPS receiver on the UAV, calculating a heading in dependence upon the starting position, the coordinates of the waypoint, and a navigation algorithm, identifying flight control instructions for flying the UAV on the heading, and transmitting the flight control instructions from the remote control device to the UAV. Figure 3 is a block diagram of an exemplary remote control device showing relations among components of included automated computing machinery. In Figure 3, remote control device (161) includes a processor (164), also typically referred to as

a central processing unit or ‘CPU.’ The processor may be a microprocessor, a programmable control unit, or any other form of processor useful according to the form factor of a particular remote control device as will occur to those of skill in the art. Other components of remote control device (161) are coupled for data transfer to 5 processor (164) through system bus (160).

Remote control device (161) includes random access memory or ‘RAM’ (166). Stored in RAM (166) an application program 152 that implements inventive methods of the present invention. In some embodiments, the application program (152) is

10 OSGi compliant and therefore runs on an OSGi services framework installed (not shown) on a JVM (not shown). In addition, software programs and further information for use in implementing methods of navigating a UAV according to embodiments of the present invention may be stored in RAM or in non-volatile memory (168). Non-volatile memory (168) may be implemented as a magnetic disk 15 drive such as a micro-drive, an optical disk drive, static read only memory (‘ROM’), electrically erasable programmable read-only memory space (‘EEPROM’ or ‘flash’ memory), or otherwise as will occur to those of skill in the art.

Remote control device (161) includes communications adapter (170) implementing

20 data communications connections (184) to other computers (162), including particularly computers on UAVs. Communications adapters implement the hardware level of data communications connections through which remote control devices communicate with UAVs directly or through networks. Examples of 25 communications adapters include modems for wired dial-up connections, Ethernet (IEEE 802.3) adapters for wired LAN connections, 802.11b adapters for wireless LAN connections, and Bluetooth adapters for wireless microLAN connections.

The example remote control device (161) of Figure 3 includes one or more input/output interface adapters (180). Input/output interface adapters in computers implement user-oriented input/output through, for example, software drivers and computer hardware for controlling output to display devices (184) such as computer display screens, as well as user input from user input devices (182) such as keypads, joysticks, keyboards, and touch screens.

Figure 4 sets forth a flow chart illustrating an exemplary method for navigating a UAV that includes receiving (402) in a remote control device a user's selection of a 10 GUI map pixel (412) that represents a waypoint for UAV navigation. The pixel has a location on the GUI. Such a GUI map display has many pixels, each of which represents at least one position on the surface of the Earth. A user selection of a pixel is normal GUI operations to take a pixel location, row and column, from a GUI input/output adapter driven by a user input device such as a joystick or a mouse. The 15 remote control device can be a traditional 'ground control station,' an airborne PDA or laptop, a workstation in Earth orbit, or any other control device capable of accepting user selections of pixels from a GUI map.

The method of Figure 4 includes mapping (404) the pixel's location on the GUI to 20 Earth coordinates (414) of the waypoint. As discussed in more detail below with reference to Figure 5, mapping (404) the pixel's location on the GUI to Earth coordinates of the waypoint (414) typically includes mapping pixel boundaries of the GUI map to corresponding Earth coordinates and identifying a range of latitude and a range of longitude represented by each pixel. Mapping (404) the pixel's location on the GUI to Earth coordinates of the waypoint (414) also typically includes locating a 25 region on the surface of the Earth in dependence upon the boundaries, the ranges, and the location of the pixel on the GUI map.

The method of Figure 4 also includes receiving (408) a starting position from a GPS receiver on the UAV. In fact, the remote control device is receiving downlink telemetry that includes a steady stream of GPS positions of the UAV. Receiving a

5 starting position therefore is typically carried out by taking the current position of the UAV when the user selects the pixel as the starting position.

The method of Figure 4 also includes calculating (410) a heading in dependence upon the starting position, the coordinates of the waypoint, and a navigation algorithm.

10 Methods of calculating a heading are discussed in detail below in this specification.

The method of Figure 4 includes identifying (418) flight control instructions for flying the UAV on the heading. Flight control instructions are specific commands that affect the flight control surfaces of the UAV. That is, instructions to move the 15 flight control surfaces to affect the UAV's flight causing the UAV to turn, climb, descend, and so on. As an aid to further explanation, an exemplary method of identifying flight control instructions for flying on a calculated heading is provided:

- receive new calculated heading from navigation algorithms
- 20 • read current heading from downlink telemetry
- if current heading is left of the calculated heading, identify flight control instruction: AILERONS LEFT 30 DEGREES
- 25 • if current heading is right of the calculated heading, identify flight control instruction: AILERONS RIGHT 30 DEGREES

- monitor current heading during turn
- when current heading matches calculated heading, identify flight control instruction: FLY STRAIGHT AND LEVEL

5

The method of Figure 4 includes transmitting (420) the flight control instructions from the remote control device to the UAV. Transmitting (420) the flight control instructions from the remote control device to the UAV may be carried out by use of

10 any data communications protocol, including, for example, transmitting the flight control instructions as form data, URI encoded data, in an HTTP message, a WAP message, an HDML message, or any other data communications protocol message as will occur to those of skill in the art.

15

Macros

Although the flow chart of Figure 4 illustrates navigating a UAV to a single waypoint, as a practical matter, embodiments of the present invention typically support navigating a UAV along a route having many waypoints, including a final

20 waypoint and one or more intermediate waypoints. That is, methods of the kind illustrated in Figure 4 may also include receiving user selections of a multiplicity of GUI map pixels representing waypoints, where each pixel has a location on the GUI and mapping each pixel location to Earth coordinates of a waypoint.

25 Such methods for navigating a UAV can also include assigning one or more UAV instructions to each waypoint and storing the coordinates of the waypoints and the UAV instructions in computer memory on the remote control device. A UAV

instruction typically includes one or more instructions for a UAV to perform a task in connection with a waypoint. Exemplary tasks include turning on or off a camera installed on the UAV, turning on or off a light installed on the UAV, orbiting a waypoint, or any other task that will occur to those of skill in the art.

5

UAV instructions to perform tasks in connection with a waypoint may be encoded in, for example, XML (the eXtensible Markup Language) as shown in the following exemplary XML segment:

```
10      <UAV-Instructions>
          <macro>
              <waypoint> 33° 44' 10" N 30° 15' 50" W </waypoint>
              <instruction> orbit </instruction>
              <instruction> videoCameraON </instruction>
15      <instruction> wait30minutes </instruction>
              <instruction> videoCameraOFF </instruction>
              <instruction> nextWaypoint </instruction>
          </macro>
          <macro> </macro>
20      <macro> </macro>
          <macro> </macro>
          <UAV-instructions>
```

This XML example has a root element named ‘UAV-instructions.’ The example contains several subelements named ‘macro.’ One ‘macro’ subelement contains a waypoint location representing an instruction to fly to 33° 44' 10" N 30° 15' 50" W. That macro subelement also contains several instructions for tasks to be performed

when the UAV arrives at the waypoint coordinates, including orbiting around the waypoint coordinates, turning on an on-board video camera, continuing to orbit for thirty minutes with the camera on, turning off the video camera, and continuing to a next waypoint. Only one macro set of UAV instructions is shown in this example,

5 but that is not a limitation of the invention. In fact, such sets of UAV instructions may be of any useful size as will occur to those of skill in the art.

Exemplary methods of navigating a UAV also include flying the UAV to each waypoint in accordance with one or more navigation algorithms and operating the

10 UAV at each waypoint in accordance with the UAV instructions for each waypoint. Operating the UAV at the waypoint in accordance with the UAV instructions for each waypoint typically includes identifying flight control instructions in dependence upon the UAV instructions for each waypoint. Flight control instructions identified in dependence upon the UAV instructions for each waypoint typically include specific
15 flight controls to move the flight control surfaces of the UAV causing the UAV to fly in accordance with the UAV instructions. For example, in the case of a simple orbit, a flight control instruction to move the ailerons and hold them at a certain position causing the UAV to bank at an angle can effect an orbit around a waypoint.

20 Operating the UAV at the waypoint in accordance with the UAV instructions for each way point typically includes transmitting the flight control instructions from the remote control device to the UAV. Transmitting the flight control instructions from the remote control device to the UAV may be carried out by use of any data communications protocol, including, for example, transmitting the flight control
25 instructions as form data, URI encoded data, in an HTTP message, a WAP message, an HDML message, or any other data communications protocol message as will occur to those of skill in the art.

Pixel Mapping

For further explanation of the process of mapping pixels' locations to Earth coordinates, Figure 5 sets forth a block diagram that includes a GUI (502) displaying a map (not shown) and a corresponding area of the surface of the Earth (504). The GUI map has pixel boundaries identified as Row₁, Col₁; Row₁, Col₁₀₀; Row₁₀₀, Col₁₀₀; and Row₁₀₀, Col₁. In this example, the GUI map is assumed to include 100 rows of pixels and 100 columns of pixels. This example of 100 rows and columns is presented for convenience of explanation; it is not a limitation of the invention. GUI maps according to embodiments of the present invention may include any number of pixels as will occur to those of skill in the art.

The illustrated area of the surface of the Earth has corresponding boundary points identified as Lat₁, Lon₁; Lat₁, Lon₂; Lat₂, Lon₂; and Lat₂, Lon₁. This example assumes that the distance along one side of surface area (504) is 100 nautical miles, so that the distance expressed in terms of latitude or longitude between boundary points of surface area (504) is 100 minutes or 1° 40'.

In typical embodiments, mapping a pixel's location on the GUI to Earth coordinates of a waypoint includes mapping pixel boundaries of the GUI map to Earth coordinates. In this example, the GUI map boundary at Row₁, Col₁ maps to the surface boundary point at Lat₁, Lon₁; the GUI map boundary at Row₁, Col₂ maps to the surface boundary point at Lat₁, Lon₂; the GUI map boundary at Row₂, Col₂ maps to the surface boundary point at Lat₂, Lon₂; the GUI map boundary at Row₂, Col₁ maps to the surface boundary point at Lat₂, Lon₁.

Mapping a pixel's location on the GUI to Earth coordinates of a waypoint typically also includes identifying a range of latitude and a range of longitude represented by each pixel. The range of latitude represented by each pixel may be described as $(Lat_2 - Lat_1) / N_{rows}$, where $(Lat_2 - Lat_1)$ is the length in degrees of the vertical side of the

5 corresponding surface (504), and N_{rows} is the number of rows of pixels. In this example, $(Lat_2 - Lat_1)$ is $1^\circ 40'$ or 100 nautical miles, and N_{rows} is 100 rows of pixels. The range of latitude represented by each pixel in this example therefore is one minute of arc or one nautical mile.

10 Similarly, the range of longitude represented by each pixel may be described as $(Lon_2 - Lon_1) / N_{cols}$, where $(Lon_2 - Lon_1)$ is the length in degrees of the horizontal side of the corresponding surface (504), and N_{cols} is the number of columns of pixels. In this example, $(Lon_2 - Lon_1)$ is $1^\circ 40'$ or 100 nautical miles, and N_{cols} is 100 columns of pixels. The range of longitude represented by each pixel in this example therefore is
15 one minute of arc or one nautical mile.

Mapping a pixel's location on the GUI to Earth coordinates of a waypoint typically also includes locating a region on the surface of the Earth in dependence upon the boundaries, the ranges, and the location of the pixel on the GUI map. The region is

20 the portion of the surface corresponding the pixel itself. That region is located generally by multiplying in both dimension, latitude and longitude, the range of latitude and longitude by column or row numbers of the pixel location on the GUI map. That is, a latitude for the surface region of interest is given by Expression 1.

25 (Exp. 1) $Lat_1 + P_{row} ((Lat_2 - Lat_1) / N_{rows})$

In Expression 1:

Lat₁ is the latitude of an origin point for the surface area (504) corresponding generally to the GUI map,

5 P_{row} is the row number of the pixel location on the GUI map, and

((Lat₂ - Lat₁) / N_{rows}) is the range of latitude represented by the pixel.

Similarly, a longitude for the surface region of interest is given by Expression 2.

10

(Exp. 2) Lon₁ + P_{col} ((Lon₂ - Lon₁) / N_{cols})

In Expression 2:

15

Lon₁ is the longitude of an origin point for the surface area (504) corresponding generally to the GUI map,

P_{col} is the column number of the pixel location on the GUI map, and

20

((Lon₂ - Lon₁) / N_{cols}) is the range of longitude represented by the pixel.

Referring to Figure 5 for further explanation, Expressions 1 and 2 taken together identify a region (508) of surface area (504) that corresponds to the location of pixel (412) mapping the pixel location to the bottom left corner (506) of the region (508).

25

Advantageously, however, many embodiments of the present invention further map the pixel to the center of the region by adding one half of the length of the region's sides to the location of the bottom left corner (506).

More particularly, locating a region on the surface of the Earth in dependence upon the boundaries, the ranges, and the location of the pixel on the GUI map, as illustrated by Expression 3, may include multiplying the range of longitude represented by each 5 pixel by a column number of the selected pixel, yielding a first multiplicand; and multiplying the range of longitude represented by each pixel by 0.5, yielding a second multiplicand; adding the first and second multiplicands to an origin longitude of the GUI map.

10 (Exp. 3)
$$\text{Lon}_1 + P_{\text{col}} ((\text{Lon}_2 - \text{Lon}_1) / N_{\text{cols}}) + 0.5((\text{Lon}_2 - \text{Lon}_1) / N_{\text{cols}})$$

In Expression 3, the range of longitude represented by each pixel is given by $((\text{Lon}_2 - \text{Lon}_1) / N_{\text{cols}})$, and the first multiplicand is $P_{\text{col}} ((\text{Lon}_2 - \text{Lon}_1) / N_{\text{cols}})$. The second multiplicand is given by $0.5((\text{Lon}_2 - \text{Lon}_1) / N_{\text{cols}})$.

15 Similarly, locating a region on the surface of the Earth in dependence upon the boundaries, the ranges, and the location of the pixel on the GUI map, as illustrated by Expression 4, typically also includes multiplying the range of latitude represented by each pixel by a row number of the selected pixel, yielding a third multiplicand; 20 multiplying the range of latitude represented by each pixel by 0.5, yielding a fourth multiplicand; and adding the third and fourth multiplicands to an origin latitude of the GUI map.

(Exp. 4)
$$\text{Lat}_1 + P_{\text{row}} ((\text{Lat}_2 - \text{Lat}_1) / N_{\text{rows}}) + 0.5((\text{Lat}_2 - \text{Lat}_1) / N_{\text{rows}})$$

25 In Expression 4, the range of latitude represented by each pixel is given by $((\text{Lat}_2 - \text{Lat}_1) / N_{\text{rows}})$, and the third multiplicand is $P_{\text{row}} ((\text{Lat}_2 - \text{Lat}_1) / N_{\text{rows}})$. The fourth

multiplicand is given by $0.5((\text{Lat}_2 - \text{Lat}_1) / N_{\text{rows}})$. Expressions 3 and 4 taken together map the location of pixel (412) to the center (510) of the located region (508).

5

Navigation on a Heading to a Waypoint

An exemplary method of navigating in accordance with a navigation algorithm is explained with reference to Figures 6 and 7. Figure 6 sets forth a flow chart illustrating an exemplary method of navigating a UAV in accordance with a

10 navigation algorithm, and Figure 7 sets forth a line drawing illustrating a flight path produced by application of the method of Figure 6.

The method of Figure 6 includes periodically repeating (610) the steps of, receiving (602) in the remote control device from the GPS receiver a current position of the

15 UAV, and calculating (604) a new heading from the current position to the waypoint.

The method of Figure 6 also includes identifying (606) flight control instructions for flying the UAV on the new heading, and transmitting (608), from the remote control device to the UAV, the flight control instructions for flying the UAV on the new heading. In this method, if $\text{Lon}_1, \text{Lat}_1$ is taken as the current position, and $\text{Lon}_2, \text{Lat}_2$ is taken as the waypoint position, then the new heading may be calculated generally as the inverse tangent of $((\text{Lat}_2 - \text{Lat}_1) / (\text{Lon}_2 - \text{Lon}_1))$.

Figure 7 shows the effect of the application of the method of Figure 6. In the example of Figure 7, a UAV is flying in a cross wind having cross wind vector (708).

25 Curved flight path (716) results from periodic calculations according to the method of Figure 6 of a new heading straight from a current location to the waypoint. Figure 7 shows periodic repetitions of the method of Figure 6 at plot points (710, 712, 714).

For clarity of explanation, only three periodic repetitions are shown, although that is not a limitation of the invention. In fact, any number of periodic repetitions may be used as will occur to those of skill in the art.

5

Navigation with Headings set to a Cross Track Direction

A further exemplary method of navigating in accordance with a navigation algorithm is explained with reference to Figures 8 and 9. Figure 8 sets forth a flow chart illustrating an exemplary method of navigating a UAV in accordance with a

- 10 navigation algorithm, and Figure 9 sets forth a line drawing illustrating a flight path produced by application of the method of Figure 8. The method of Figure 8 includes identifying (802) a cross track between the starting point and the waypoint. A cross track is a fixed course from a starting point directly to a waypoint. If $\text{Lon}_1, \text{Lat}_1$ is taken as the position of a starting point, and $\text{Lon}_2, \text{Lat}_2$ is taken as the waypoint position, then a cross track is identified by $\text{Lon}_1, \text{Lat}_1$ and $\text{Lon}_2, \text{Lat}_2$. A cross track has a direction, a 'cross track direction,' that is the direction straight from a starting point to a waypoint, and it is often useful to characterize a cross track by its cross track direction. The cross track direction for a cross track identified by starting point $\text{Lon}_1, \text{Lat}_1$ and waypoint position $\text{Lon}_2, \text{Lat}_2$ may be calculated generally as the
- 15 inverse tangent of $((\text{Lat}_2 - \text{Lat}_1) / (\text{Lon}_2 - \text{Lon}_1))$.

The method of Figure 8 includes periodically repeating (810) the steps of receiving (804) in the remote control device from the GPS receiver a current position of the UAV, and calculating (806) a shortest distance between the current position and the

- 25 cross track. If the shortest distance between the current position and the cross track is greater than a threshold distance (808), the method of Figure 8 includes transmitting (812) flight control instructions that pilot the UAV toward the cross track, and, when

the UAV arrives at the cross track, transmitting (814) flight control instructions that pilot the UAV in a cross track direction toward the waypoint.

Figure 9 illustrates calculating a shortest distance between the current position and a cross track. In the example of Figure 9, calculating a shortest distance between the current position and a cross track includes calculating the distance from a current position (912) to the waypoint (704). In the example of Figure 9, the distance from the current position (912) to the waypoint (704) is represented as the length of line (914). For current position $\text{Lon}_1, \text{Lat}_1$ and waypoint position $\text{Lon}_2, \text{Lat}_2$, the distance from a current position (912) to the waypoint (704) is given by the square root of $(\text{Lat}_2 - \text{Lat}_1)^2 + (\text{Lon}_2 - \text{Lon}_1)^2$.

In this example, calculating a shortest distance between the current position and a cross track also includes calculating the angle (910) between a direction from the current position (912) to the waypoint (704) and a cross track direction. In the example of Figure 9, the direction from the current position (912) to the waypoint (704) is represented as the direction of line (914). In the example of Figure 9, the cross track direction is the direction of cross track (706). The angle between a direction from the current position to the waypoint and a cross track direction is the difference between those directions.

In the current example, calculating a shortest distance between the current position and a cross track also includes calculating the tangent of the angle between a direction from the current position to the waypoint and a cross track direction and multiplying the tangent of the angle by the distance from the current position to the waypoint.

Figure 9 also shows the effect of the application of the method of Figure 8. In the

example of Figure 9, a UAV is flying in a cross wind having cross wind vector (708). The flight path (904) results from periodic calculations according to the method of Figure 8 of a shortest distance between a current position and the cross track (706), flying the UAV back to the cross track and then flying in the direction of the cross track whenever the distance from the cross track exceeds a predetermined threshold distance.

5

Headings set to Cross Track Direction with Angular Thresholds

10 A further exemplary method of navigating in accordance with a navigation algorithm is explained with reference to Figures 10 and 11. Figure 10 sets forth a flow chart illustrating an exemplary method of navigating a UAV in accordance with a navigation algorithm, and Figure 11 sets forth a line drawing illustrating a flight path produced by application of the method of Figure 10.

15

In the method of Figure 10, piloting in accordance with a navigation algorithm includes identifying (1002) a cross track having a cross track direction between the starting point and the waypoint. As described above, a cross track is identified by a position of a starting point and a waypoint position. For a starting point position of

20 Lon₁, Lat₁ and a waypoint position of Lon₂, Lat₂, a cross track is identified by Lon₁, Lat₁ and Lon₂, Lat₂. In addition, it is often also useful to characterize a cross track by its cross track direction. The cross track direction for a cross track identified by starting point Lon₁, Lat₁ and waypoint position Lon₂, Lat₂ may be calculated generally as the inverse tangent of $((Lat_2 - Lat_1) / (Lon_2 - Lon_1))$.

25

In the method of Figure 10, navigating a UAV in accordance with a navigation algorithm includes periodically repeating (1010) the steps of receiving (1004) in the

remote control device from the GPS receiver a current position and a current heading of the UAV, and calculating (1006) an angle between the direction from the current position to the waypoint and a cross track direction. If the angle is greater than a threshold angle (1008), the method of Figure 10 includes transmitting (1012) flight

5 control instructions that pilot the UAV toward the cross track, and, upon arriving at the cross track, transmitting (1014) flight control instructions that pilot the UAV in the cross track direction toward the waypoint.

Transmitting (1012) flight control instructions that pilot the UAV toward the cross

10 track is carried out by transmitting flight control instructions to turn to a heading no more than ninety degrees from the cross track direction, turning to the left if the current position is right of the cross track and to the right if the current position is left of the cross track. Transmitting (1014) flight control instructions that pilot the UAV in the cross track direction toward the waypoint transmitting flight control
15 instructions to turn the UAV to the cross track direction and then flying straight and level on the cross track direction.

Figure 11 shows the effect of the application of the method of Figure 10. In the example of Figure 11, a UAV is flying in a cross wind having cross wind vector

20 (708). The flight path (1104) results from periodically transmitting flight control instructions to fly the UAV, according to the method of Figure 10, back to the cross track and then in the direction of the cross track whenever an angle between the direction from the current position to the waypoint and a cross track direction exceeds a predetermined threshold angle.

25

In many embodiments of the method of Figure 10, the threshold angle is a variable whose value varies in dependence upon a distance between the UAV and the

waypoint. In typical embodiments that vary the threshold angle, the threshold angle is increased as the UAV flies closer to the waypoint. It is useful to increase the threshold angle as the UAV flies closer to the waypoint to reduce the risk of excessive ‘hunting.’ That is, because the heading is the cross track direction, straight

5 to the WP rather than cross-wind, if the angle remains the same, the distance that the UAV needs to be blown off course to trigger transmitting flight control signals instructing the UAV to return to the cross track gets smaller and smaller until the UAV is flying to the cross track, turning to the cross track direction, getting blown immediately across the threshold, flying back the cross track, turning to the cross

10 track direction, getting blown immediately across the threshold, and so on, and so on, in rapid repetition. Increasing the threshold angle as the UAV flies closer to the waypoint increases the lateral distance available for wind error before triggering the transmission of flight instructions to return to the cross track, thereby reducing this risk of excessive hunting.

15

Navigation on a Course to a Waypoint

A further exemplary method of navigating in accordance with a navigation algorithm is explained with reference to Figures 12, 12A, and 13. Figure 12 sets forth a flow

20 chart illustrating an exemplary method of navigating a UAV in accordance with a navigation algorithm. Figure 12A sets forth a line drawing illustrating a method of calculating a heading with a cross wind to achieve a particular ground course. And Figure 13 sets forth a line drawing illustrating a flight path produced by application of the method of Figure 12.

25

In the method of Figure 12, navigating a UAV in accordance with a navigation algorithm includes periodically repeating (1212) the steps of receiving (1202) in the

remote control device from the GPS receiver a current position of the UAV, calculating (1204) a direction to the waypoint from the current position, and calculating (1206) a heading in dependence upon wind speed, wind direction, air speed, and the direction to the waypoint. The method of Figure 12 also includes

5 transmitting (1208) flight control instructions for turning the UAV to the heading, and transmitting (1210) flight control instructions for flying the UAV on the heading.

Figure 12A illustrates calculating (1206) a heading in dependence upon wind speed, wind direction, air speed, and the direction to the waypoint. Figure 12A sets forth a

10 line drawing illustrating relations among several pertinent vectors, a wind velocity (1222), a resultant velocity (1224), and a UAV's air velocity (1226). A velocity vector includes a speed and a direction. These vectors taken together identify wind speed, wind direction, air speed, and the direction to the waypoint. In the example of Figure 12A, the angle B is a so-called wind correction angle, an angle which

15 subtracted from (or added to, depending on wind direction) a direction to a waypoint yields a heading, a compass heading for a UAV to fly so that its resultant ground course is on a cross track. A UAV traveling at an air speed of 'a' on heading (D - B) in the presence of a wind speed 'b' with wind direction E will have resultant ground speed 'c' in direction D.

20

In Figure 12A, angle A represents the difference between the wind direction E and the direction to the waypoint D. In Figure 12A, the wind velocity vector (1222) is presented twice, once to show the wind direction as angle E and again to illustrate angle A as the difference between angles E and D. Drawing wind velocity (1222) to

25 form angle A with the resultant velocity (1224) also helps explain how to calculate wind correction angle B using the law of sines. Knowing two sides of a triangle and the angle opposite one of them, the angle opposite the other may be calculated, in this

example, by $B = \sin^{-1}(b(\sin A) / a)$. The two known sides are airspeed ‘a’ and wind speed ‘b.’ The known angle is A, the angle opposite side ‘a,’ representing the difference between wind direction E and direction to the waypoint D. Calculating a heading, angle F on Figure 12A, is then carried out by subtracting the wind correction angle B from the direction to the waypoint D.

Figure 13 shows the effect of the application of the method of Figure 12. In the example of Figure 13, a UAV is flying in a cross wind having cross wind vector (708). Curved flight path (1316) results from periodic calculations according to the method of Figure 12 of a new heading straight whose resultant with a wind vector is a course straight from a current location to the waypoint. Figure 13 shows periodic repetitions of the method of Figure 12 at plot points (1310, 1312, 1314). For clarity of explanation, only three periodic repetitions are shown, although that is not a limitation of the invention. In fact, any number of periodic repetitions may be used as will occur to those of skill in the art.

Navigation on a Course set to a Cross Track Direction

A further exemplary method of navigating in accordance with a navigation algorithm is explained with reference to Figures 14 and 15. Figure 14 sets forth a flow chart illustrating an exemplary method of navigating a UAV in accordance with a navigation algorithm, and Figure 15 sets forth a line drawing illustrating a flight path produced by application of the method of Figure 14.

The method of Figure 14 includes identifying (1402) a cross track and calculating (1404) a cross track direction from the starting position to the waypoint. In the method of Figure 14, navigating a UAV in accordance with a navigation algorithm is

carried out by periodically repeating (810) the steps of receiving (1406) in the remote control device from the GPS receiver a current position of the UAV, and calculating (1408) a shortest distance between the cross track and the current position. If (1410) the shortest distance between the cross track and the current position is greater than a
5 threshold distance, the method of Figure 14 includes transmitting (1412) flight control instructions for piloting the UAV to the cross track. When the UAV arrives at the cross track, the method of Figure 14 includes receiving (1414) in the remote control device from the GPS receiver a new current position of the UAV, calculating (1416), in dependence upon wind speed, wind direction, air speed, and the cross track
10 direction, a new heading, transmitting (1418) flight control instructions for turning the UAV to the new heading, and transmitting (1420) flight control instructions for flying the UAV on the new heading.

Figure 15 shows the effect of the application of the method of Figure 14. In the
15 example of Figure 15, a UAV is flying in a cross wind having cross wind vector (708). The flight path (1504) results from periodic calculations according to the method of Figure 14 of a shortest distance between a current position and the cross track (706), transmitting flight control instructions to the UAV to fly back to the cross track, and, upon arriving at the cross track, calculating a new heading and
20 transmitting flight control instructions to the UAV to fly on the new heading.

It will be understood from the foregoing description that modifications and changes may be made in various embodiments of the present invention without departing from its true spirit. The descriptions in this specification are for purposes of illustration
25 only and are not to be construed in a limiting sense. The scope of the present invention is limited only by the language of the following claims.